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Possibility of Deformation of Billet with Various Internal Structure in KOBO Extrusion

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Abstract The potential of KOBO unconventional extrusion of metallic materials based on phenomenon of changing the path of plastic deformation with use of cyclic oscillation of the die by given angle and frequency has been presented in this paper. This process is used to change material properties by fragmentation of grains without preheating the billet and press parts with significantly lower extrusion force in comparison to conventional process. Various types of billets (various metallic materials in the form of: solid initial material, condensed chips, layered composite material) were used during the experimental tests to analyze the plastic flow of the material and the possibility of plastic deformation of various metallic materials such as aluminum alloys, magnesium alloys and copper in order to obtain a product with a complex shape in the KOBO process, using dies with different geometries. Mechanical properties, microstructure, scheme of plastic flow and extrusion force were examined during experimental work. KOBO extrusion can be considered as a more cost-effective process than conventional extrusion.

Introduction

The KOBO method [1] is an unconventional method of metallic materials extrusion using the phenomenon of changing the path of plastic deformation by introducing a tool (die) into cyclic oscillations (around its axis) by a given angle and at a predetermined frequency (Fig.1).

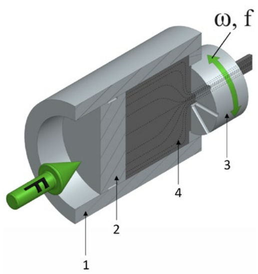


Fig. 1 KOBO extrusion pattern 1- container sleeve, 2- dummy billet, 3- die, 4 – billet

The method can be classified as an SPD method, but unlike most of the methods of this group, which only aim to change the material properties by grain fragmentation, it also allows for the shaping of the desired geometry products, as in conventional extrusion processes. The main advantages of the KOBO method are the considerable reduction in plastic work and thus the reduction of the extrusion force, and the possibility of implementing the process without preheating the billet and tools, with the possibility of high deformation [2].

The method can be considered as more cost-effective than conventional extrusion. According to literature sources [2], besides the possibility to extrude hard aluminum alloys such as 7075T6 in cold process with high extrusion ratio which is impossible in conventional cold extrusion, it gives the possibility to extrude aluminum alloys with five times higher extrusion speed in hot (300ºC) process with similar extrusion force [2].

The KOBO method is an efficient, low-energetic method for the recycling of chips [3] both from light metal alloys such as aluminum or magnesium, and from alloys of hardly deformable materials such as titanium [4].

In literature [2,5] the mechanism of material flow in the KOBO extrusion process is described as radial with concentration of plasticization in the zone located directly at the face of the die. There is, however, no study on the direct influence of the geometrical features of the tool and in particular on the face of the die for the final extrusion effect in the KOBO process including the effect of plasticization and the flow pattern of the material or changes in the force parameters. Therefore, research in this field is justified.
Cyclic change in the path of deformation resulting from the movement of the die increases the ductility of the material and inhibits the formation and propagation of cracks [6,7]. The selection of these parameters is essential in achieving a spectacular effect by reducing the extrusion force (compared to the traditional concurrent or even counter-rotating extrusion process) and increasing the homogeneity of the microstructure on the cross-section and longitudinal cross-section of the extruded product. The improvement of properties is obtained by reducing the grain size [8] and high plastic deformation [9]. With regard to the analysis of microstructure transformation, attention should be paid to the demonstrated effects of macrostructure and microstructure level, taking into account elements of crystallographic defects at the level of analysis of the effects of generation and movement of dislocation [10].
According to the works of various authors [e.g. 11-14] the ranges of parameters used in the KOBO process are: the angle of oscillation of the die from 6º up to 20° and the frequency of rotational movement of the die from 3Hz to 10Hz. The temperature of the process fluctuated in the range of 20ºC (no preheating) to 400ºC. After the extrusion process, the products were cooled with water or air.
The state of knowledge shows great potential of the KOBO extrusion method that allows to deform products with different billet structure, complex shapes of the cross-section of final products. This allows to increase the possibility of plastic forming of extrudate with effects impossible to achieve in conventional extrusion processes, such as the favorable microstructure of products, the effect of fragmentation and unification of the microstructure and the beneficial significant reduction of the extrusion force. This paper presents the effects of research on this process using various types of input materials, i.e. solid materials, condensed chips and layered composites.

Experimental Work

The investigation was conducted using different types of initial metallic billets: various metals such as solid initial material (aluminum and magnesium alloys), condensed chips (aluminum and magnesium alloys), and layered initial material (aluminum/copper). Mechanical properties, microstructure, scheme of plastic flow and extrusion force were examined during experimental work To compare the final result of extrusion of solid metal and compacted chips the 2024, 7075 alloys in the form of chips from real manufacturing process and in the form of solid material were used in the investigation. Layered composite billet (aluminum and copper) allowed to describe specific plastic flow in the KOBO extrusion process using KOBO press and dies with different geometry (Fig.2).

a) b)

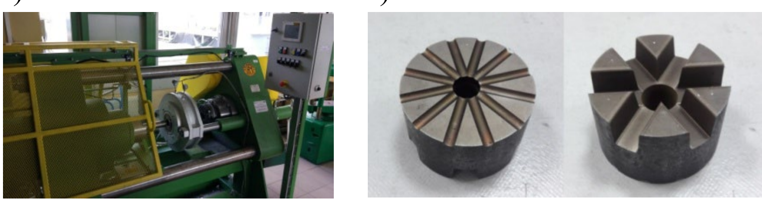


Fig. 2 a) KOBO press 2,5MN used in the experiment b) examples of extrusion dies

To analyze the plastic flow and the possibility of plastic deformation of various metallic materials such as aluminum alloys, magnesium alloys and copper in order to obtain various products of complex shape in the KOBO process, using dies with different geometries, the results of KOBO extrusion of solid billets (Fig.3a), compacted chips (Fig.4) and layered composed billet (Fig.5) were compared.

Analysis of the internal structure of the extruded product and the identification of the plastic flow character using different layers of the billet allowed for an adequate assessment of the mechanical behavior of the metal under the conditions of KOBO extrusion.
Samples for metallographic tests were taken from the front, middle and end part of the obtained products. The first sample (initial fragment) was taken from the product area for which the process was already stabilized. The axial and longitudinal sections of the selected rod sections and the butt - retained part of the billet and the product of the last extrusion stage, remaining from each of the extrusion tests in the longitudinal section in the product axis (Fig.3b) were subjected to microscopic observations.

Materials
Different types of billets have been used in the experimental work to analyze plastic flow and plastic deformability of various metallic materials.

Solid billet

a) b)

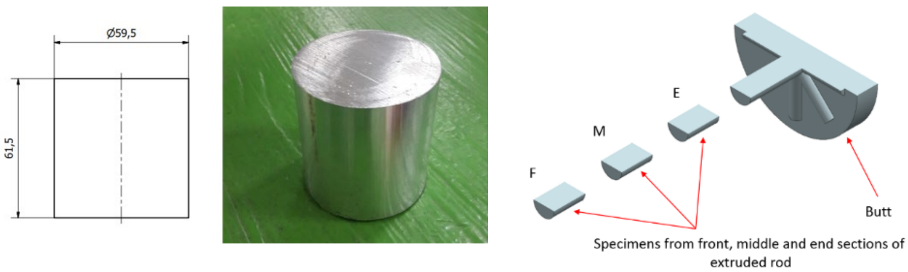


Fig. 3 a) Solid billet, b)Examined specimens from the extruded product for identification of plastic flow, microstructure and mechanical properties

The adequate selection of KOBO extrusion parameters was made on the basis of literature sources and own experience for each of the cases, which is very important from the point of view of the quality of the obtained product with the required microstructure and mechanical properties.
KoBo process parameters for extrusion of solid billet are as follows:
- Extrusion rate 0.1mm/s
- Frequency of oscillation of the die 3-7Hz
- Angle of oscillation of the die ±6°
- Cooling of the extrudate on the press run with water at ambient temperature

Compacted chips as billet
The machining chips coming from the manufacturing processes, contained coolant and lubricant residue. They were not given any cleaning after being produced. In the first stage of the experiment the chips were compacted. They were put into a special container and pressed on a vertical hydraulic press under pressure of 0.3MN. The obtained metal briquettes (Fig.4), 59mm in diameter and 105mm in length, were used as billets for KOBO method.

a) b)

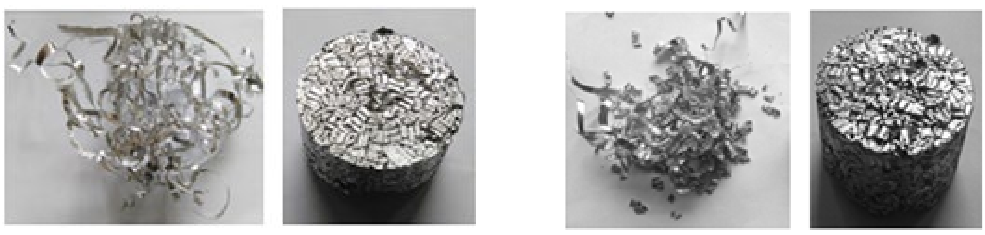


Fig. 4 Chips of 2024 (a) and 7075 alloys (b) and aluminium briquettes made of them as initial material for KOBO process (billet)

KoBo process parameters for extrusion of chips:
- Extrusion rate 0.1mm/s
- Frequency of oscillation of the die 5Hz
- Angle of oscillation of the die ±6°
- Cooling of the extrudate on the press run with water at ambient temperature

Layered composite billet

In order to identify the plastic flow character of the KOBO extrusion process, billets consisting of alternating 5mm aluminum alloy 7075 T6 discs and 0.1mm thick copper (M1E) film (Fig. 5) were prepared. The aluminum alloy discs after being cut with a coolant were cleaned using an alcohol-based cleaner and dried. Discs of copper sheet, directly before assembling the materials in packages, were immersed in nitric acid and dried to remove the surface layer. Three dies of different face geometry were prepared: Type I – 8 deep radial grooves on face (3mm deep), Type II – 12 shallow grooves on face (1mm deep), Type III – 8 deep radial grooves on face and spherical prechamber. In all cases, other dimensions were kept the same, 10mm circular die aperture with 3mm long die bearings.

a) b)

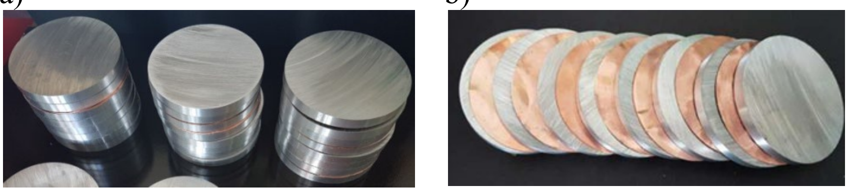


Fig. 5 Billets prepared for experiment a) billets prepared for extrusion, b) sequence of billet components

KoBo process parameters for extrusion of composed billet:
- Extrusion rate 0.1mm/s
- Frequency of oscillation of the die 5Hz
- Angle of oscillation of the die ±°6
- Cooling of the extrudate on the press run with water at ambient temperature

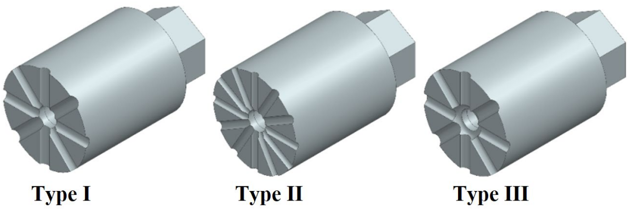


Fig. 6 Extrusion dies of different geometry used in investigations

Mechanical properties (tensile tests, hardness)

Based on the experimental results obtained in the process of extrusion of solid metals and alloys, the presented experiments were conducted with the amplitude of the die rotation angle equal to ±6°. The frequency of die oscillation was selected in the range of 5÷8Hz. In order to keep constant kinetics of the extrusion process (constant force and rate of extrusion) the frequency of the oscillation of die was a variable. The extrusion process was conducted at room temperature with the use of non-heated briquettes as billets. The thermal effect (an increase of temperature) mainly resulted from deformation. The extrusion rate was in the range of 0.2-0.25mm/s.

As an example of the result of extrusion process a 10mm wire was obtained with the extrusion ratio λ=36. The obtained products were tested for their mechanical properties in a uniaxial tensile test and Vickers hardness test. (Fig.7, Fig.8)

Fig. 7 shows the diagram of tensile tests on wires obtained by consolidation of chips of 2024 and 7075 in the process of concurrent extrusion by KOBO method, whereas Table 1, Table 2, Table 3 present the determined mechanical properties.

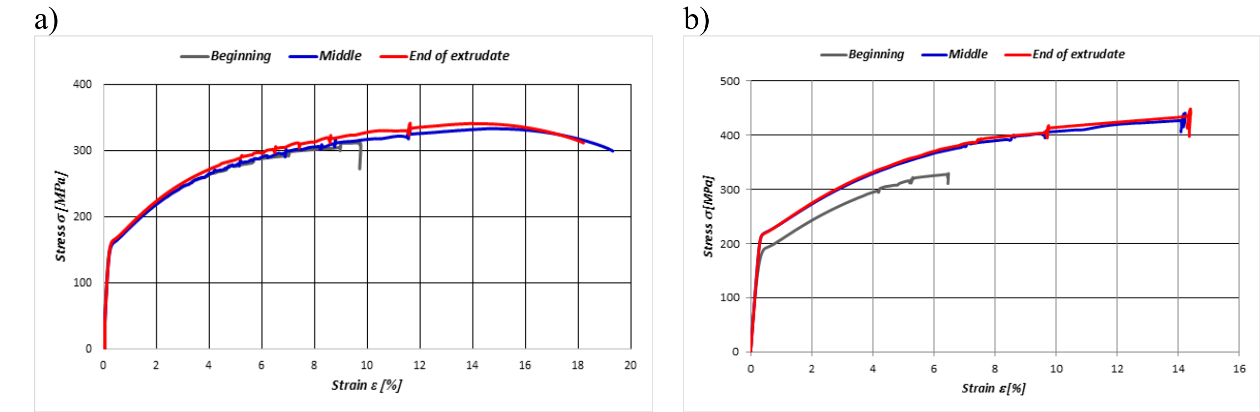


Fig. 7 Tensile curves of φ=10mm wires after 2024 (a), and 7075 (b) chips consolidation by KoBo method

Figure 8 shows the results of Vickers hardness tests with the load of 1N, in accordance with ASTM E407-07 of the sample taken from the middle part of extrudate for 2024 and 7075 alloys.

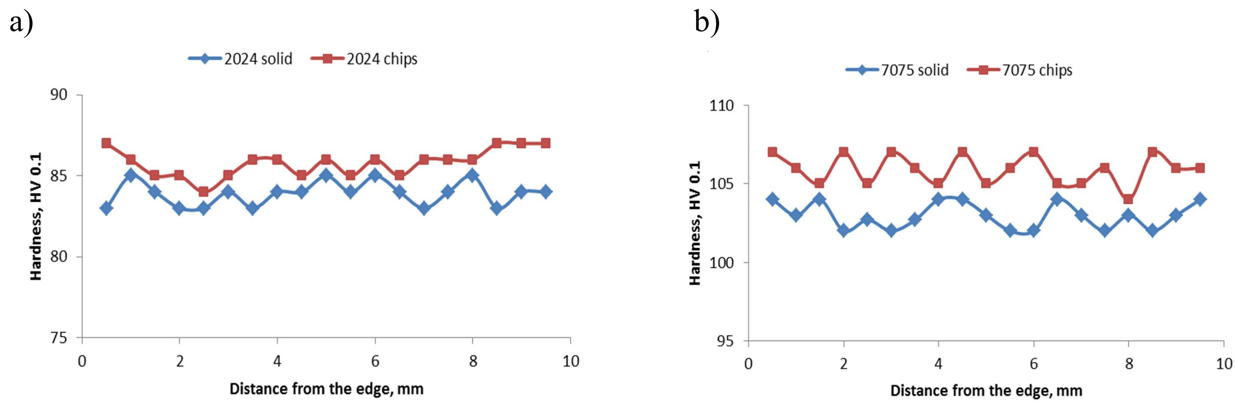


Fig. 8. Hardness distribution in the extrudate made of chips and solid materials by KOBO method (middle part of extrudate) for 2024 alloy (a) and 7075 alloy (b)

Table 1. Mechanical properties of extrudates made of chips obtained after extrusion by KOBO method (average values from three results of test samples)

Test piece/Properties	R_m [MPa]	$R_{0,2}$ [MPa]	A [%]
2024 – beginning of extrudate	290	161	9,2
2024– middle of extrudate	299	165	19,3
2024 – end of extrudate	306	171	18,2
7075 – beginning of extrudate	309	190	6,46
7075– middle of extrudate	385	210	14,2
7075 – end of extrudate	392	219	14,3

Table 2 Mechanical properties of extrudate made of solid material extruded by KOBO Method (average values from three test pieces)

Test piece/Properties	Rm [MPa]	R0,2 [MPa]	A [%]
2024 – beginning of extrudate	286	163	9,7
2024– middle of extrudate	292	171	8,2
2024 – end of extrudate	296	196	4,9
7075 – beginning of extrudate	295	189	4,7
7075– middle of extrudate	295	214	4,4
7075 – end of extrudate	303	209	3,4

The Vickers hardness tests prove that after chip consolidation by KOBO method the material has better hardness compared with hardness of solid material (Table 3).

Table 3 Hardness test results for solid material and after chips consolidation

Hardness [HV 0,1] (average value)			
Solid material		**material made of chips**	
2024	83,89	2024	85,78
7075	102,96	7075	105,89

By comparing mechanical properties of the material from the extruded consolidated chips in a tensile test, it can be observed that the tensile strength increases as the distance from the beginning of the extrudate grows. The yield point is similar with a significant difference at the beginning part of the wire. Elongation at specific parts of the wire has shown a considerable fall at the beginning of the extrudate. For comparison of the effect of extrusion of consolidated chips the results of extrusion of solid material were given.

KOBO extrusion using the billet with alternating layers of the main material (aluminum alloy 7075) and Cu foil allowed to evaluate the mechanical behavior of the metal in the process and to model the flow of material. The mechanical properties of the extruded specimens according to the specific die geometry of the I, II and III type (Fig. 6) show little difference in both the Young's modulus and the contractual yield strength and tensile strength due to the same Al7075 / Cu extruded material. KOBO process parameters

Table 4 Results of the uniaxial tensile test

Mechanical properties *Diet ype*	**E** [GPa]	$\mathbf{R_{0.2}}$ [MPa]	$\mathbf{R_m}$ [MPa]
Extruded rod, *die type III*, test 1	73	387	491
Extruded rod, *die type III*, test 2	72	390	522
Extruded rod, *die type II*, test 1	73	383	470
Extruded rod, *die type II,* test 2	70	373	483
Extruded rod, *die type I*, test 1	73	378	497
Extruded rod, *die type I*, test 2	73	381	470
7075 T6 Al. alloy	72	460	520
Copper M1E	110	33	210

The presented results show the purpose of searching for design solutions of dies adapted to the extrusion of a given type of materials by KOBO method.

Microstructure

The results of macro and microstructural observations of profiles of the extrudate produced by solid aluminum alloy 2024 and 7075 during low-temperature KOBO extrusion are presented in Fig. 9.

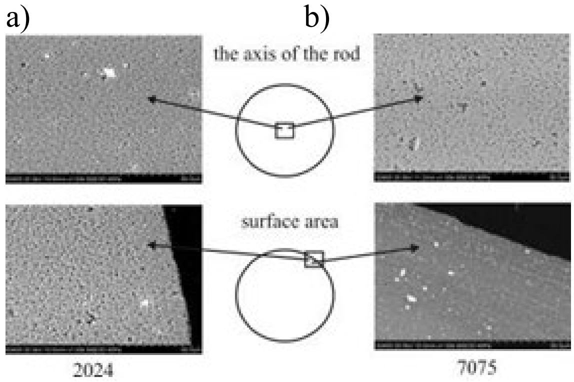


Fig. 9 Microstructures of rod obtained from solid 2024 (a), and 7075 (b) aluminum alloy (mag. 1000x)

The extruded rods from solid material - 2024 and 7075 macro, and microstructure are highly homogeneous. The microstructure of the alloy 2024 consists of the matrix - the grains of the solid solution α−Al and the relatively large, undissolved molecules of the intermetallic phase (Cu, Fe, Mn) Al_6 and $CuMgAl_2$ phase particles in the form of spheroidal shaped particles.

The microstructure of the 7075 alloy consists of a matrix of solid alloys in aluminum and fine precipitates of irregular $MgZn_2$ phase particles and large precipitations of the $FeAl_3$ intermetallic phase, insoluble precipitates (Fe, Mn) Al_6 at the grain boundaries and the Mg_2Si dispersion strengthening phase.

In the area of the outside diameter, plastic strain lines are visible, typical for the extrusion process, no cracks, impurities or other discontinuities were found. The plastic forming operations applied did not cause major changes in the morphology of the alloy microstructure components.

The results of macro – and microstructural observations of profiles of the compact produced by aluminum alloy 2024 and 7075 chips consolidation during low-temperature KOBO extrusion are shown in Fig. 10. Observations of the macrostructure showed that in the case of extruded rods from chips 2024, the heterogeneity, unevenly appearing in the cross-section is visible - the largest occur in the near-surface area, the smallest in the area of the rod axis. Some examples of inhomogeneity have the appearance of small discontinuities (arrows). The 7075 structure is characterized by the presence of ring-shaped heterogeneities. In this case, there are no visible discontinuities.

Based on the observation of the microstructure of rods extruded from material from consolidated chips, it was found that in the surface areas there are heterogeneities in the form of strongly deformed, elongated bands, without a clear boundary of separation (Fig. 10c).

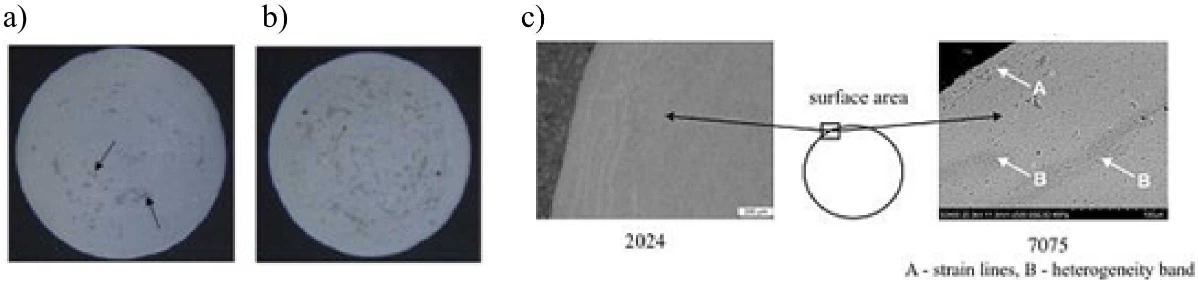


Fig. 10 Macrostructures of rod obtained from solid 2024 (a) and 7075 (b) aluminum alloy chips (mag. 6x), Microstructures of extruded rod obtained from 2024 and 7075 (c) aluminum alloy chips (mag. 100x)

The study of the flow scheme was based on the analysis of the characteristic layers of the billet - the markers of the flow pattern (Fig. 11).

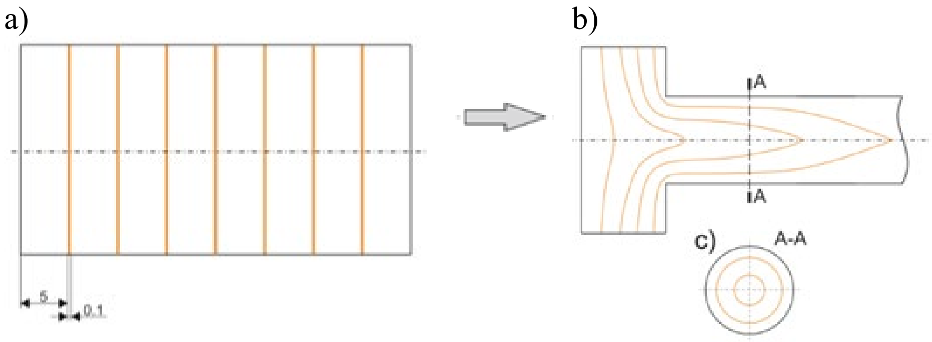


Fig. 11 Diagram of analysis of characteristic lines - marker layers, a) Billet material - Aluminum and copper foil slices stacked alternately, b) Longitudinal section of the butt and the product, c) Cross section of the product.

Physical flow modeling under conditions of the KOBO process allows to determine the influence of the type of dies with different geometrical parameters on the scheme of the plastic flow of the metal. Billets made of alternating slices of 7075 T6 aluminum and copper (M1E) were used in composed billet. The process was performed using dies of different face geometry without heating the billets and press parts. Copper layers were used as markers to identify the plastic flow pattern and plastic flow zones while demonstrating the possibility of obtaining an Al-Cu metallic composite.
The analysis of the physical modeling effects in the KOBO process is based on the results identifying the distribution of lines and characteristic zones in cross sections and longitudinal sections of the rod and butt (input material from the end of the extrusion), including part of the billet and product (Fig.12) and, for example, shown in Table 5.

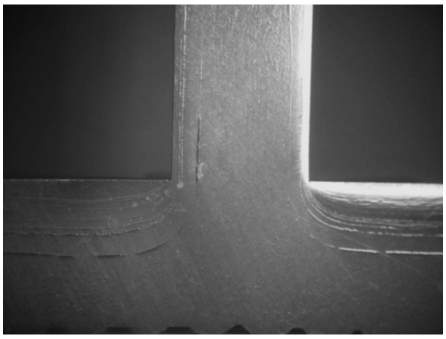
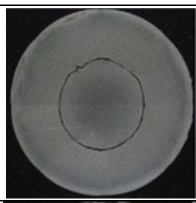
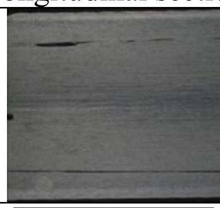
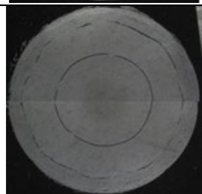
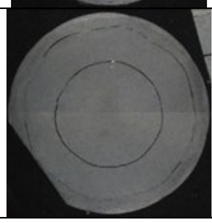
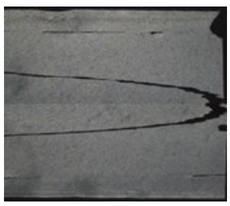


Fig. 12 Macrostructure of the butt - the ends of extruded material - obtained in the KOBO process.

Table 5 Axial cross-sections and longitudinal sections of KOBO products

	Die- type I	
	Axial cross-section	Longitudinal section
Product front part		
Product middle part		
Product end part		

Observations of the microstructure (Fig.13) showed that in all tested samples, there was no defect in the copper-aluminum alloy boundary and the microstructure in the zone of the phase separation showed the combination of the two metals. The banding of the microstructure is visible in longitudinal sections. Microstructure of the alloy is fine-grained (average grain diameter 1÷ 4µm), and it consists of the intermetallic reinforcing phases in the matrix of the solid aluminum solution.

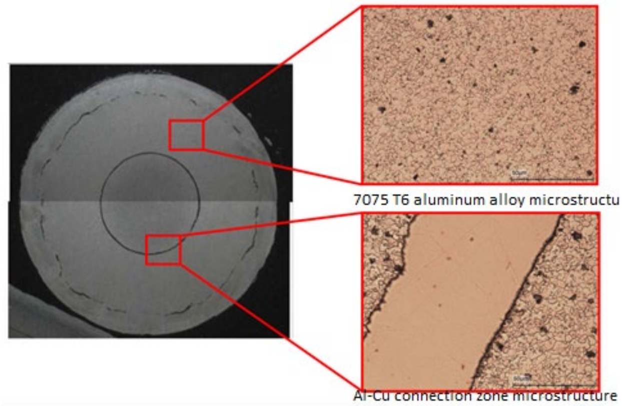


Fig. 13. Microstructure in cross section of 7075 / Cu extruded rod

Specimens from extruded products as well as butts were tested for macro and microstructure analysis and mechanical properties. All specimens were characterized by favorable, homogeneous fine-grained microstructure throughout the volume of the product. Interface zone between Al and Cu is inseparable, devoid of defects. Obtained composite material has very good mechanical properties.
Modification of the features of tools for the KOBO extrusion process has direct influence on the process parameters and the plastic deformation of the billet material.
In order to realize the main principle of the developed method, which is cyclic oscillation of the die, the construction of the KOBO press differs from conventional press construction.
Occurrence of the minimum dead zone or its absence, laminar and non-laminar flow zones in the plasticization zone (swirls of the marker lines), allows for evaluation of uniformity of deformation in the area of the plasticization zone and in the extruded product depending on the geometry of the die.

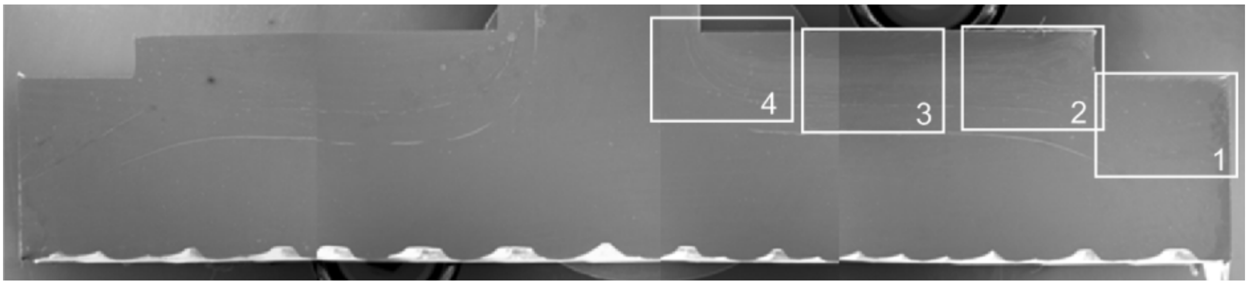
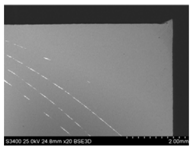
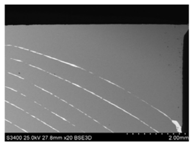
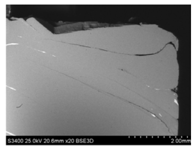
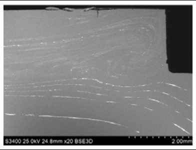
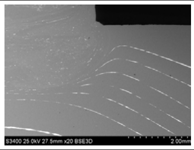
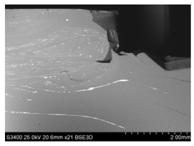
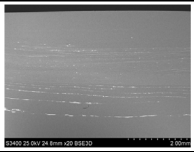
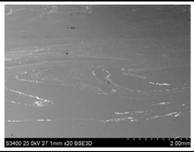
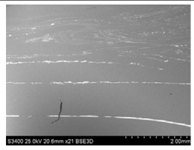
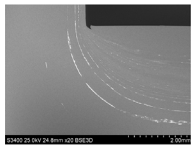
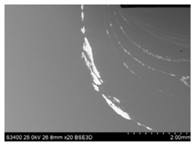
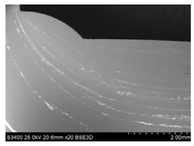


Fig. 14 Butt macrostructure, die type I

The macrostructure of the characteristic areas revealing the plastic scheme diagram is shown in Table 6. Comparative analysis of these corresponding zones shows a significant difference in pattern depending on the geometry of the die.

Table 6 Flow pattern in butt areas according to fig. 14 (mag.20x) for the 3 types of used dies.

	Die type		
Flow scheme identyfication area	**I**	**II**	**III**
1			
2			
3			
4			

KoBo extrusion force

Parameters of Kobo process (die oscillation frequency, angle of oscillation, extrusion rate) and internal structure of a billet (solid, chips, composite) have big influence on extrusion force (Fig. 15, Table 7).

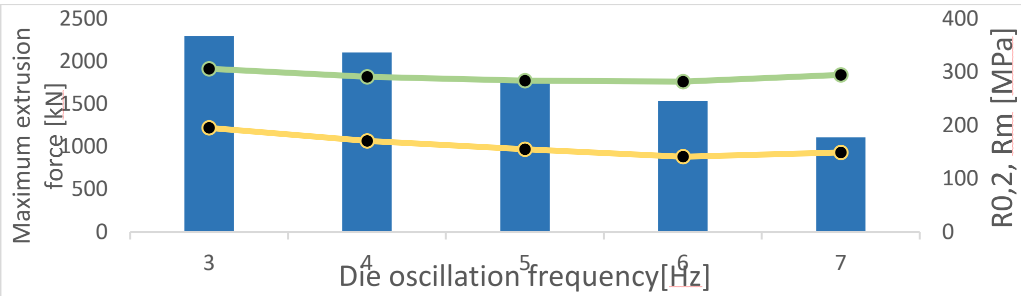


Fig. 15 Maximum extrusion force and mechanical properties of the extrudate in relation to die oscillation frequency.

The process of extrusion of compacted machining chips resulted in their consolidation and it was conducted at lower force in comparison to the extrusion of solid material (Table 7).

Table 7 Maximum extrusion force and mechanical properties of extrudate made in extrusion of solid billets and compacted chips

Material	**Max. extrusion force [kN]**
2024 solid billet	2300
2024 chips briquette	2100
7075 solid billet	1700
7075 chips briquette	1370

Oscillation Frequency [Hz]	**Max. Extrusionforce [kN]**	**$Y_{0.2}$ [MPa]**	**R_m [MPa]**
3	2298	195,2	306,2
4	2106	170,7	291
5	1776	155,2	284,1
6	1535	141	282
7	1109	149	294,9

Considering mechanical and structural aspects of the products during extrusion of Al/Cu layered composite billet from the extrusion force point of view , the most preferred flow pattern is obtained using a type III die, which is confirmed by the images of areas 3 and 4, and the smallest recorded extrusion force (Fig.16, Table 8).

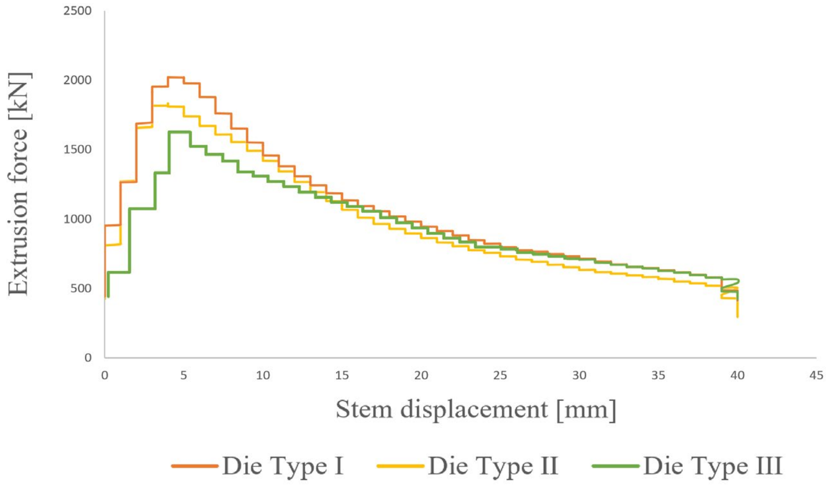


Fig. 16 KoBo Extrusion force vs. stem displacement using 3 types (I, II, III) of the dies

Table 8 Registered extrusion forces in the KOBO process using matrices of different geometries.

Die type	Max. extrusion force
I	2020 kN
II	1830 kN
III	1670 kN

The geometric features of KoBo extrusion dies with different geometries have influence on the nature of plastic flow of the billet material and final structural, mechanical and geometrical characteristics of the extruded product and the level of extrusion force.
The presented results show the purpose of searching for design solutions of dies adapted to the extrusion of a given type of materials by KOBO method.

Conclusions

The results of using various types of billets (various initial metallic materials in the form of: solid material, condensed chips, layered initial material) in the investigations of KOBO extrusion process demonstrate the unconventional plastic flow pattern and big possibility of plastic deformation of various metallic materials such as aluminum alloys, magnesium alloys and copper to obtain products using dies with different geometries.
High mechanical properties as well as small grained microstructure of extruded product were obtained after extrusion of solid and composite billet. Obtaining a very good bonding of layers as a result of the process gives the possibility to produce composite materials with different geometrical arrangement of the components.
The KoBo extrusion using different die geometries showed significant differences in the flow scheme depending on the type of die. The relationship between the used type of die and the force of extrusion was demonstrated. From the dies tested, the most preferred flow pattern was obtained using a Type III die, which is confirmed by the lowest extrusion force.
The properties are the same in the entire volume of the product, there is no difference between front, middle and end part of the profiles.
KoBo method allows for full consolidation of dispersed chips of 2024 and 7075 aluminium alloys and allows for obtaining long products by cold forming.

The KoBo process of manufacturing products is both material and energy-saving and harmless to the natural environment. Presented consolidation process of chips may be applicable not only for recycling of chip of aluminium and its alloys, but also for chips of other metals (e.g. magnesium and its alloys, titanium and its alloys).
The presence of impurities in chips after machining does not pose a significant difficulty for obtaining a solid product in the process of extrusion by KOBO method, however their good purification fosters consolidation. That method has a tremendous technological potential and has an extensive range of process control options.
The identified in KoBo extrusion superplastic type of metal flow enables to obtain a high quality product, even with complex shapes. Low flow stress and lack of strain hardening under high strain conditions, which characterizes superplastic flow, allows for deformation of hard alloys at low temperatures.
Modification of the die geometry affects the extrusion forces making them lower.
KoBo extrusion can be considered as a more cost-effective process than conventional extrusion.

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